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CONTINUOUS BROADBAND MONITORING OF STRAIN CHANGES NEAR ACTIVE FAULTS IN SOUTHERN CALIFORNIA

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Abstract

This grant has supported us to continue operating the facilities at Piñon Flat Observatory (PFO) that measure crustal deformation in Southern California for periods from seconds to years. At this site, close to the San Jacinto and San Andreas faults, we have long-base strainmeters and tiltmeters whose sensitivity and stability are unmatched anywhere else. The long time over which these data have been gathered, and the multiple measurements available, give the results a strength that is difficult to achieve in this field.

These measurements are relevant to the NEHRP program because they contribute to our understanding of the seismic cycle and how stresses accumulate on faults: for this, there is no substitute for a detailed, extended time history. The measurements from PFO now encompass a lengthy period of enhanced seismic activity (from 1986 on), including the two largest earthquakes in southern California since 1952. The PFO measurements continue to provide a check on any possible strain anomalies throughout Southern California.

Specific activities supported by this grant include:

- Operation of PFO: that is, providing high-quality and timely records of deformation fluctuations by running the long-base instruments and making ancillary measurements. In particular, monitoring the strain changes resulting from the 1992 Landers and 1999 Hector Mine earthquakes, both of which produced a rapid (though decaying) postseismic strain change. The Landers earthquake's postseismic signal was followed by a slower reversal in strain rate and a return to secular strain accumulation; it is too early to know if this pattern will be repeated after the Hector Mine shock, although the data to date suggest not.
- Provision of facilities that serve as a shared resource for the development and testing of emerging new technologies of geophysical interest. Having the components of PFO in place (land, power, shelters, recording) makes this much easier and less expensive than would otherwise be the case. The most recent work has involved various tests of environmental effects on GPS measurements.

The grant supports power, replacement parts, and salaries of technical staff, and is only a part of the PFO support, with other funds coming from the Scripps Director's office and the Southern California Earthquake Center.

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1. Introduction

This grant provided funds to operate continuous, stable, and precise strain and tilt measurements in Southern California, at Piñon Flat Observatory (PFO), between the central San Jacinto fault and the Coachella Valley segment of the San Andreas fault. (Under separate NEHRP and SIO funding we have support to operate a strainmeter at Durmid Hill (DHL), very close to the San Andreas fault.)

The continued operation of PFO provides a time history of deformation changes, measured with the most comprehensive, sensitive, and stable methods available. Such a time history, especially over durations that begin to be a significant fraction of the seismic cycle, provides the only picture available of how stresses in the crust accumulate—something we must understand in order to estimate seismic hazard reliably. A systematic development process (unavoidably lengthy for such long-term measurements) has resulted in the instruments at PFO being able to measure deformation in ways not equalled anywhere else—and has also resulted in a record of such changes that is longer (for example) than the entire history of GPS measurements in California. By characterizing the deformation field so well in southern California, we provide a guide to what can be expected in other regions; as our recent contributions to the SCIGN GPS array have shown, others who make less precise observations using continuous GPS can be guided by what we continue to learn about techniques for measuring deformations.

2. Recent Results

A number of papers in the last few years have described results that utilize data from PFO (Abercrombie *et al.*, 1995; Gomberg and Agnew, 1996; Hart *et al.*, 1996; Johnson *et al.*, 1995; Kohl and Levine, 1995; Langbein *et al.*, 1995; Zumberge and Wyatt, 1998). In this section we describe more recent results, especially the deformation changes associated with the Hector Mine earthquake in 1999—relatively close to PFO.

2.1. The Hector Mine Earthquake

The second large earthquake close to PFO in a decade was the Hector Mine event, an M_w 7.1 shock 110 km away, on 1999:289:09:47 (day 289.4076), to the east of the 1992 Landers event. As happened after Landers, the occurrence of this earthquake raised concerns about possible triggering of a large earthquake on the southern San Andreas—concerns exacerbated by the occurrence of a swarm of triggered seismic events near the southern end of that fault. And, also as after Landers, we found the PFO (and even more the DHL) data playing a substantive role in decisions about what sort of warning to issue about this possible risk; we were able to use the data to provide an assurance that, while there was a pronounced aseismic response, it was decreasing with time.

In this section we describe the deformation records at PFO for this event (and also, but briefly, those at DHL). While this earthquake, like the Landers shock, produced significant post-seismic strains, the character of these has been quite different from those of the earlier event. We describe the different behaviors starting with the coseismic offsets and then going to phenomena with longer time constants.

Table 1: Hector Mine Coseismic Offsets

What	NS Strain	EW Strain	NW-SE Strain	SW-NE Strain
PFO Obs	289	167	161	
PFO Theory	412	−72	113	
DHL Obs	~1200			~1200
DHL Theory	35			−43

Theory for a source at 34.59°N 116.27°W, 13 km deep, pure right-lateral slip with strike N29°W, dip 77°, moment 5×10^{19} N-m. Units are 10^{-9} strain.

Coseismic offsets. Geodetic coverage of the Hector earthquake is, by the standards of even a few years ago, superb: 93 GPS sites with coseismic coverage within 100 km (50 within 35 km), and excellent InSAR coverage. Given all these data, the coseismic strain and tilt offsets recorded at PFO cannot be expected to have much importance for determining the actual earthquake mechanism—and this will be true for any future large earthquakes in the area. This means that the main interest of the coseismic offsets is as a (severe) test of the ability of the sensors to record the complete strain history during large dynamic strains; for smaller or more distant events, past work (Wyatt 1988) has shown that the long-base strainmeters measure coseismic offsets reliably.

So long as the alignment of the laser beam is not interrupted (which can occur during very strong shaking), the ability of the system to maintain lock during rapid strain changes depends on the system used to count interference fringes; any loss of count, like a cycle-slip in GPS, creates an ambiguity in the strain. Our current counters have a bandwidth of 1 MHz, corresponding to a strain rate of 10^{-4} s^{-1}. Such high rates are only reached for large high-frequency, locally generated waves (10^{-6} strain at 10 Hz), but not otherwise. The dynamic range of this counter (16 bits, or $\pm 3.5 \times 10^{-6}$ strain) can be exceeded only for very large strain changes. Provided that the dynamic strains and strain rates do not exceed the levels given, the coseismic strains will be recorded correctly.

Table 1 shows that two of the three LSM's at PFO have offsets in reasonable agreement with the predictions of a source model based on regional seismograms. The EW LSM does not: a consequence of poor alignment of the beam at the time of the earthquake, a problem to be remedied by installing automated beam steering. This earthquake was thus within the range of what can be recorded reliably—which in turn means that the instruments at DHL—at 140 km, more distant from the epicenter—should have given reliable measures of the coseismic offset. In fact the offsets recorded at DHL are very much larger than anything seen at PFO; this is explained by triggered slip on the nearby San Andreas fault.

Immediate Postseismic Deformation. From the discussion above, any problems in tracking strain changes will be confined to the short interval when the very large radiated energy arrives;

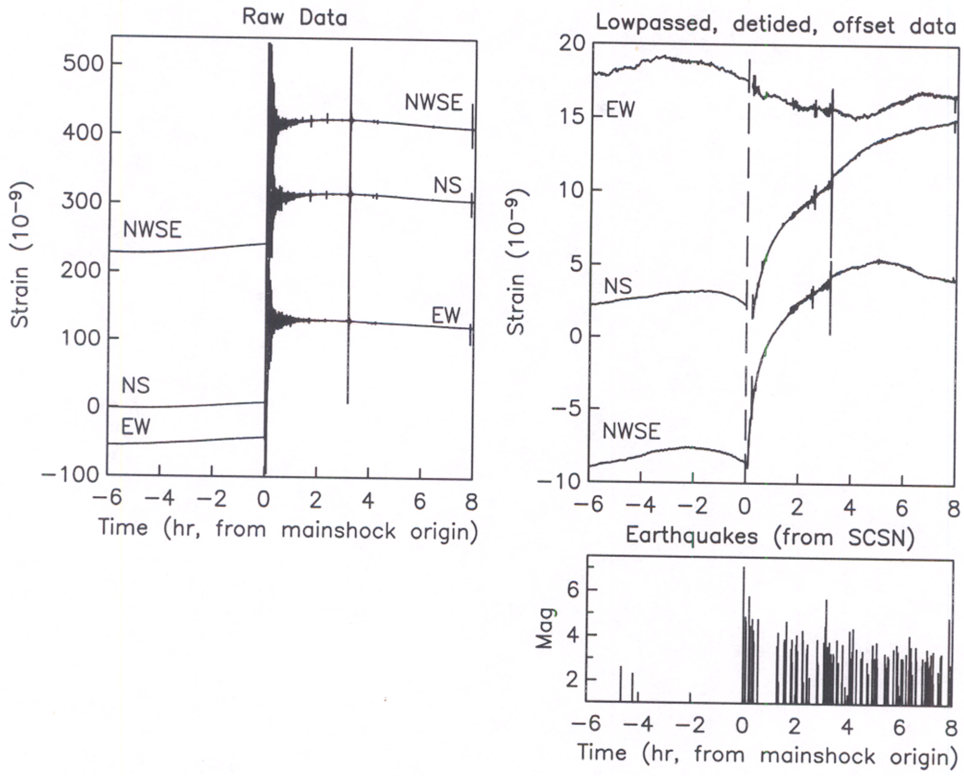

Figure 1

once the dynamic strains diminish (the coda), the records will be reliable. Simple plots of the raw data (**Figure** 1, left) are not very enlightening, since this is dominated by the dynamic strains and the offsets, and (once these are removed) the tides. The right panel of this figure shows the strains with these signals removed: the seismic energy by lowpass filtering with a corner period of 60 seconds, and the tides somewhat imperfectly because of problems in modeling thermal effects with such a short span of data. For a useful sense of scale, note the coseismic offset (~0.5 nε) from the M_L 5.7 aftershock about 3¼ hours after the mainshock.

Clearly the rapid postseismic deformation shown, while small relative to the coseismic offset, represents as much or more moment release than the aftershocks. What is perhaps most notable about this postseismic strain is the absence (on this time scale) of any response from the EW strainmeter—also true for the aftershock. An examination of the response at PFO to slip along different parts of the mapped rupture shows that a null response for EW strain would be seen for slip on the southernmost part of the rupture plane. Afterslip confined to this area cannot be the whole story, however, since this would give a larger signal on the NS than the NW-SE.

Longer-Term Postseismic Deformation. **Figure 2** and **Figure 3** show the deformation from the Hector earthquake at PFO over somewhat longer times, in both cases with another record for comparison: in **Figure 2**, the same earthquake at DHL, and in **Figure 3** a different earthquake (Landers) at PFO. Note that in comparing these figures with **Figure 1**, the offsets in the hours after the earthquake tend to be reduced in the longer time series because of the way in which the less-frequent sampling of these data (for our long time series) combines with the editing of the

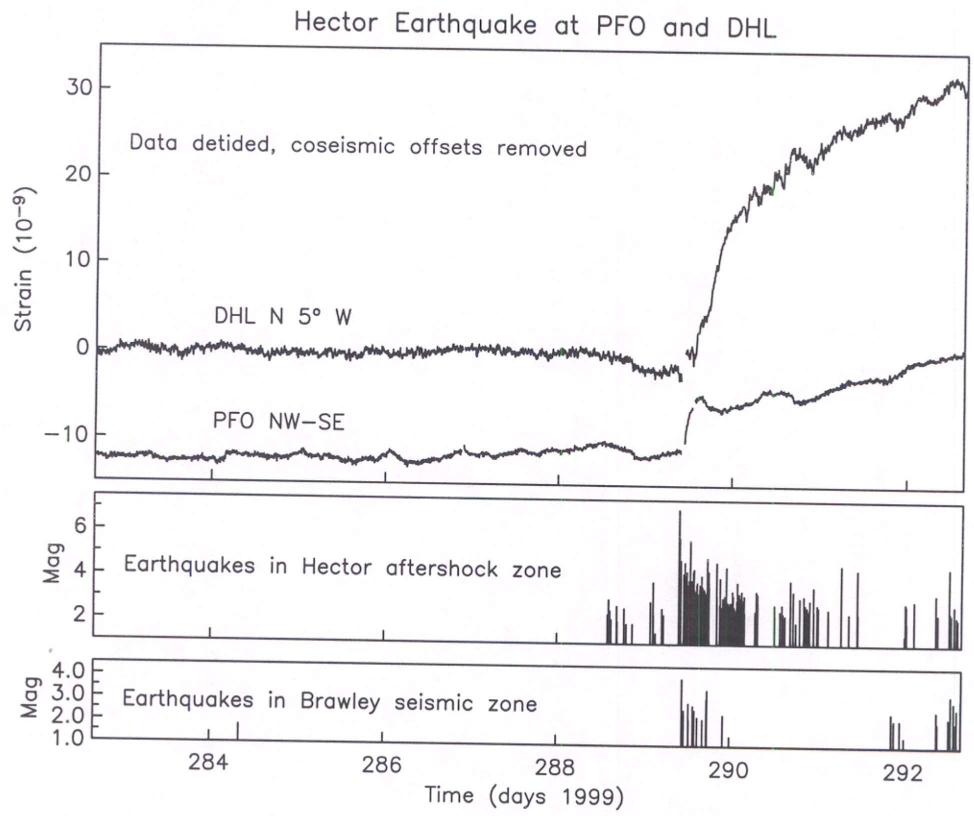

Figure 2

series; also, the detiding is different (and more effective for the longer series).

What is clear from these figures is that the postseismic deformation pattern is quite complex, and cannot be explained by simple decaying afterslip on one part of the fault. For example, the EW instrument, which shows no immediate response, does begin to show a definite signal within a day—though with a sign opposite to what would be expected for afterslip on the rupture plane. Similar complexity is also implied by the record from the NS instrument, which reverses sign after 2 days—again, the rate after this is not consistent with afterslip on the rupture. None of this resembles the uniformly monotonic decay seen in the Landers postseismic signals—and these differences provide some reassurance that this signal is not just some kind of local response of Pinyon Flat (the site, not the instruments) to strain changes and strong shaking. Over the longer times, the strainmeter we believe is reliable over these long times shows no ongoing response similar to what was seen after Landers.

At this point it seems clear that either rapid bulk relaxation or some kind of triggered slip on other faults will be necessary to explain these complex signals. Pending analysis of the postseismic GPS data it is premature to attempt any rigorous analysis based on the strain data alone—though we expect that, as in other cases, the complementary nature of the high resolution strain, and the spatial coverage of GPS, will be important to determining what has happened.

Evidence for slip triggered by the Hector earthquake comes from the strainmeters at DHL (Agnew and Wyatt, 1999). The coseismic offsets were much larger than at PFO, so large as to

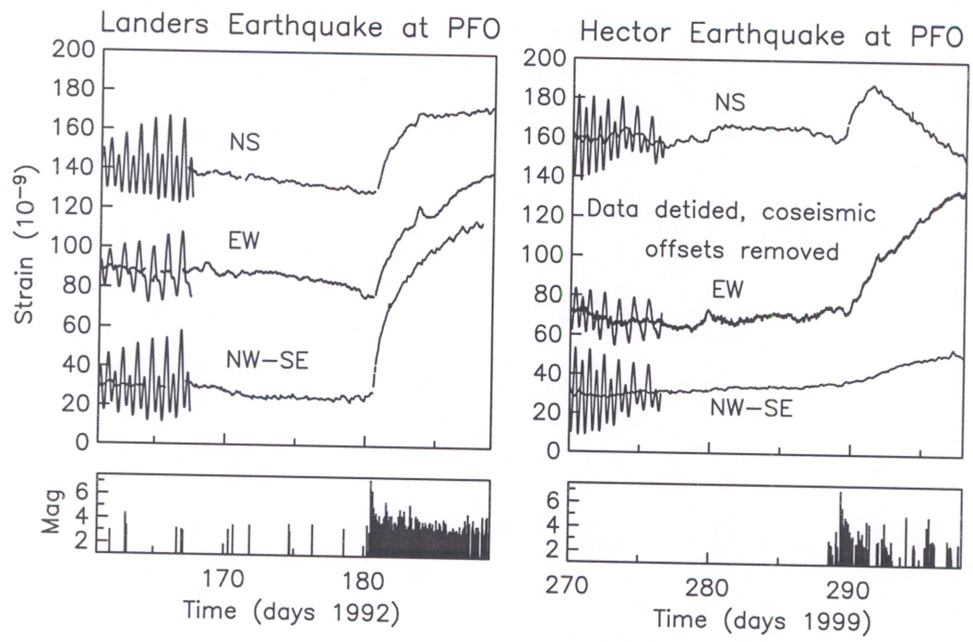

Figure 3

exceed the recorded range of the strain counter. However, examination of the part of the coda which was on-scale indicates offsets of close to 10^{-6}, far above the predicted levels for a half-space (**Table 1**). An examination of the San Andreas fault after the Hector event showed surface slip between 3 and 6 mm from Salt Creek to close to DHL (D. Yule, pers. commun., 1999); InSAR interferograms of this area (D. Sandwell, pers. commun., 1999) also showed evidence of widespread triggered slip, again not extending quite as far south as DHL. Given this, we are convinced that the greater part of the postseismic signal at DHL (**Figure 2**) is slip on the nearby San Andreas.

2.2. Other Activities

We have focussed on earthquake-related results from the sensors at PFO because this is the primary reason for support by the NEHRP. However, this support also goes to just keeping the facility open—and it continues to be true that having some dedicated space, with power and recording facilities available, enables many other investigations to take place much more easily (and less expensively) than would otherwise be true—and quite often these have relevance to NEHRP goals.

As an example of one such study, we offer results from a long-running short-baseline continuous GPS installation at PFO—and especially some recent experiments done with support from the SCIGN project. In 1989 we installed the first deeply-anchored GPS monument at PFO (PIN1); a second stable monument (PIN2) was installed 50 m to the east in 1991. PIN1 has been the primary permanent GPS site at PFO from mid-1990; PIN2 was instrumented in 1991 with a Trimble SST (on loan from UCLA), replaced in early 1997 by the standard SCIGN Ashtech receiver and choke-ring antenna.

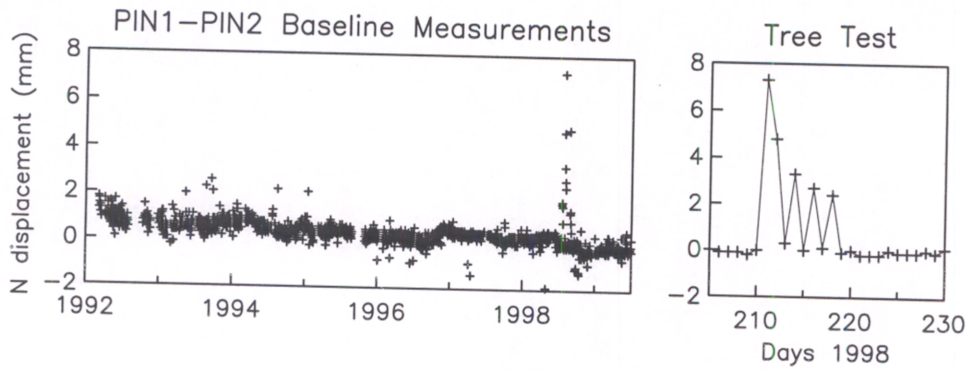

Figure 4

The high precision possible with GPS over such short baselines has made this measurement very informative; as shown in **Figure 4** (analysis by Y. Bock, G. Anderson, and H. Johnson) the data have sub-millimeter scatter, so that even very small perturbation can be identified and quantified. These data show that stable GPS monuments can be built: the secular trends are less than 0.3 mm/yr. A spectral analysis of the data shows that the horizontal components have a white-noise part with an rms of 0.17 mm. Because this value is so small, it is possible to detect the random-walk component with only these few years of data: something not possible for most globally-referenced GPS data (unless the random-walk component was very large). The random walk process is about 0.4 mm/$\sqrt{\text{year}}$ for the combination of PIN1 and PIN2; if each site contributes equally (and independently) then each monument contributes 0.7 of the total, or about 0.3 mm/$\sqrt{\text{year}}$. Since these monuments are anchored in relatively good material, this is probably a lower limit for this effect in most settings.

Having this short and well-measured baseline available has allowed us to test many possible effects on GPS measurements. The right panel of **Figure 4** shows one such test (out of many), on the effect of changes in nearby vegetation (unavoidable at many SCIGN sites). We constructed artificial trees with PVC trunks and natural branches, mounted on a sled so they could be dragged close to and away from the PIN2 antenna on alternate days. **Figure 4** shows the result in one case: a substantial offset, which decreases as the artificial tree dehydrates. We have also examined the effects of chain-link fence around the installation; this can cause an offset (larger if it is above the bottom of the choke ring), but no time variation and no significant increase in noise. We have also tested different antenna domes. This SCIGN work continues.

References

R. E. Abercrombie, D. C. Agnew, and F. K. Wyatt, "Testing a model of earthquake nucleation," *Bull. Seismol. Soc. Am.*, 85, pp. 1873-1878 (1995).

D. C. Agnew and F. K. Wyatt, "Transient strain events on the southern San Andreas fault," *EOS Trans. Am. Geophys. Union,* 80, p. F692 (1999).

J. Gomberg and D. C. Agnew, "The accuracy of seismic estimates of dynamic strains: an evaluation using strainmeter and seismometer data from Piñon Flat Observatory, California," *Bull. Seismol. Soc. Am.,* 86, pp. 212-220 (1996).

R. H. G. Hart, M. T. Gladwin, R. L. Gwyther, D. C. Agnew, and F. K. Wyatt, "Tidal calibration of borehole strainmeters: removing the effects of local inhomogeneity," *J. Geophys. Res.,* 101, pp. 25553-25571 (1996).

H. O. Johnson, F. K. Wyatt, D. C. Agnew, and W. Żurn, "Tidal tilts at Pinyon Flat, California, measured at depths of 24 and 120 meters" in *Proc. Twelfth Intl. Symposium on Earth Tides,* ed. H. T. Hsu, pp. 129-136, Science Press, Beijing (1995).

M. L. Kohl and J. Levine, "Measurement and interpretation of tidal tilts in a small array," *J. Geophys. Res.,* 100, pp. 3929-41 (1995).

J. O. Langbein, F. Wyatt, H. Johnson, D. Hamann, and P. Zimmer, "Improved stability of a deeply anchored geodetic monument for deformation monitoring," *Geophys. Res. Lett.,* 22, pp. 3533-3536 (1995).

F. Wyatt, "Measurements of coseismic deformation in southern California: 1972-1982," *J. Geophys. Res.,* 93, pp. 7923-7942 (1988).

M. A. Zumberge and F. K. Wyatt, "Optical fiber interferometers for referencing surface benchmarks to depth," *Pure Appl. Geophys.,* 152, pp. 221-246 (1998).